Dynamic Study of the P2 Discharge Line at Grand Coulee Pumping Plant

Data Transmittal Report

Water Resources Research Laboratory

by

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Data Collection

Frizell and Todd traveled to Grand Coulee and performed tests on the P2 discharge line (figure 1) at Grand Coulee Pumping Plant on October 19-20, 2005. The tests consisted of an accelerometer survey of the entire length of pipe to determine the operating deflection shapes (ODS). In addition, at the most active longitudinal location between each set of pipe supports, a circumferential ODS was also recorded. The circumferential operating deflection shapes were measured with two different accelerometer spacing (figure 2) in order to resolve higher mode shapes. The pump operating speed is 3.333 Hz and there are 9 buckets on the pump impeller yielding a blade-passing-frequency of 30 Hz.

Figure 1: View of P2 discharge line looking down from the siphon-breakers toward Lake Roosevelt.
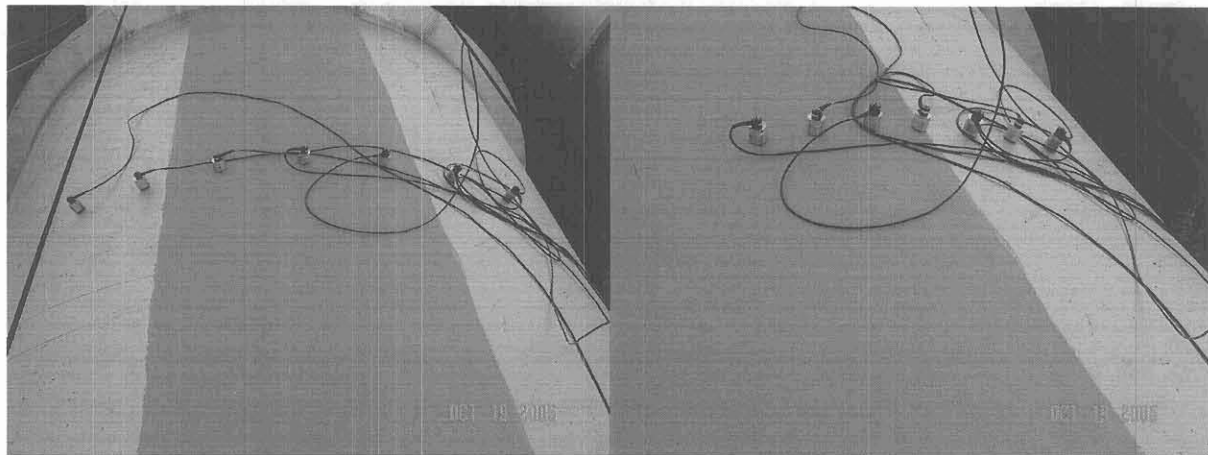
a) 60-degrees of coverage @ 10-degree spacing   b) 30-degrees of coverage @ 5-degree spacing

Figure 2: Accelerometer placements to identify circumferential operating deflection shapes.

Once the most active location along the pipes' length was located, strain gages were installed in order to measure the fluctuating stresses due to operation. Four strain gages were installed near "H" stiffener 16, figure 3 and 4. The gages were uniaxial MicroMeasurements glue-on type, 350 ohms with an active length of 0.25-in. The gages were wired into external bridge completion circuits and then wired to the data acquisition system for gage excitation and output. The data acquisition system was setup on the P3 discharge line in order to be in a vibration free location. The data acquisition system was a laptop PC controlled system, featuring an IOTech Wavebook 516 and a WKB14 and WBK16SSH for simultaneous sampling of the accelerometers and strain gages, figure 5.
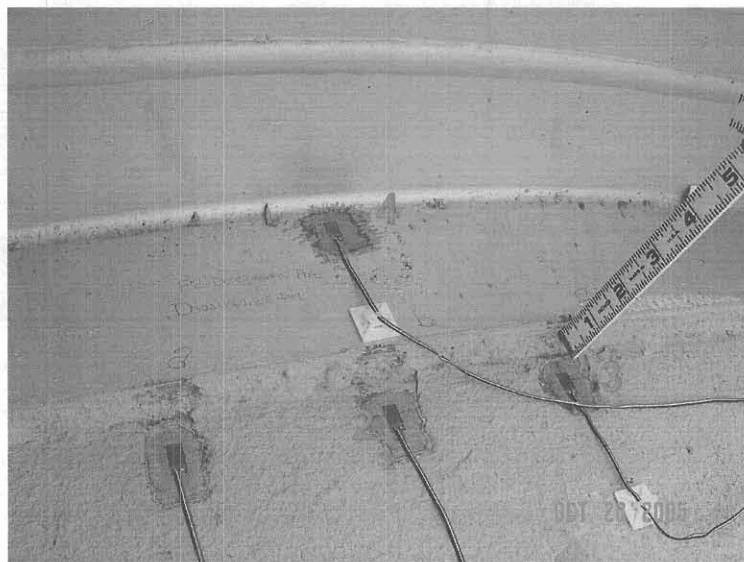
Figure 3: Four uniaxial strain gages installed along the pipe axis near and on stiffener No. 16
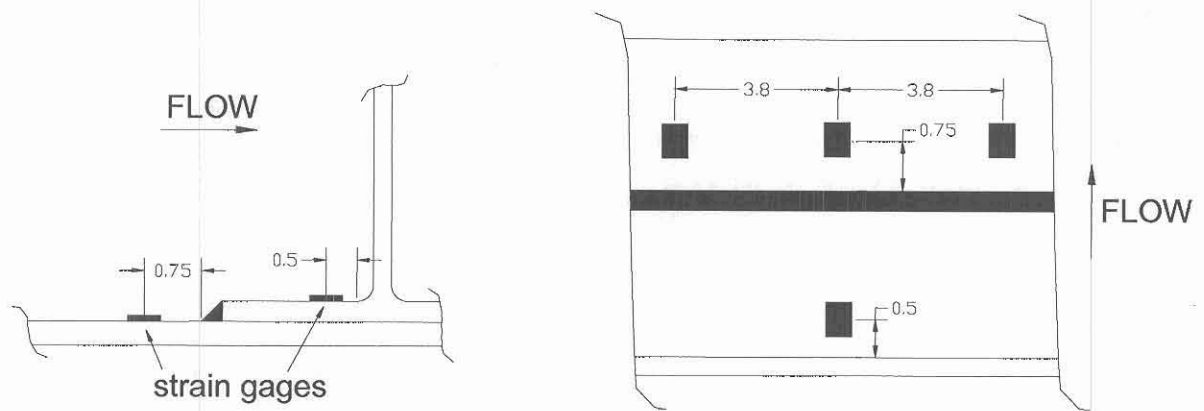
**Figure 4:** As-installed measurements for strain gages on stiffener 16.

Figure 5: Laptop-based data acquisition system for recording accelerations and stresses.

Longitudinal Accelerometer Survey

Accelerometers were spaced along the pipe axis near the crown for the six sections between supports, see figure 6 for pipe layout detail. With the pump operating, data were collected for about 1 min. Figures 7-12 show the operating deflection shapes (ODS) for pipeline sections 1-6 respectively plotted on a scale of the frequency response function (FRF) amplitudes. These FRF amplitudes are solely dependent on the magnitude of the accelerometer that is used as the reference. Each figure includes the ODS at 30 Hz and 60 Hz. Along with the operating deflection shapes, the one minute spectral averages of the accelerations are noted for both 30- and 60-Hz at the location chosen to perform the circumferential testing.
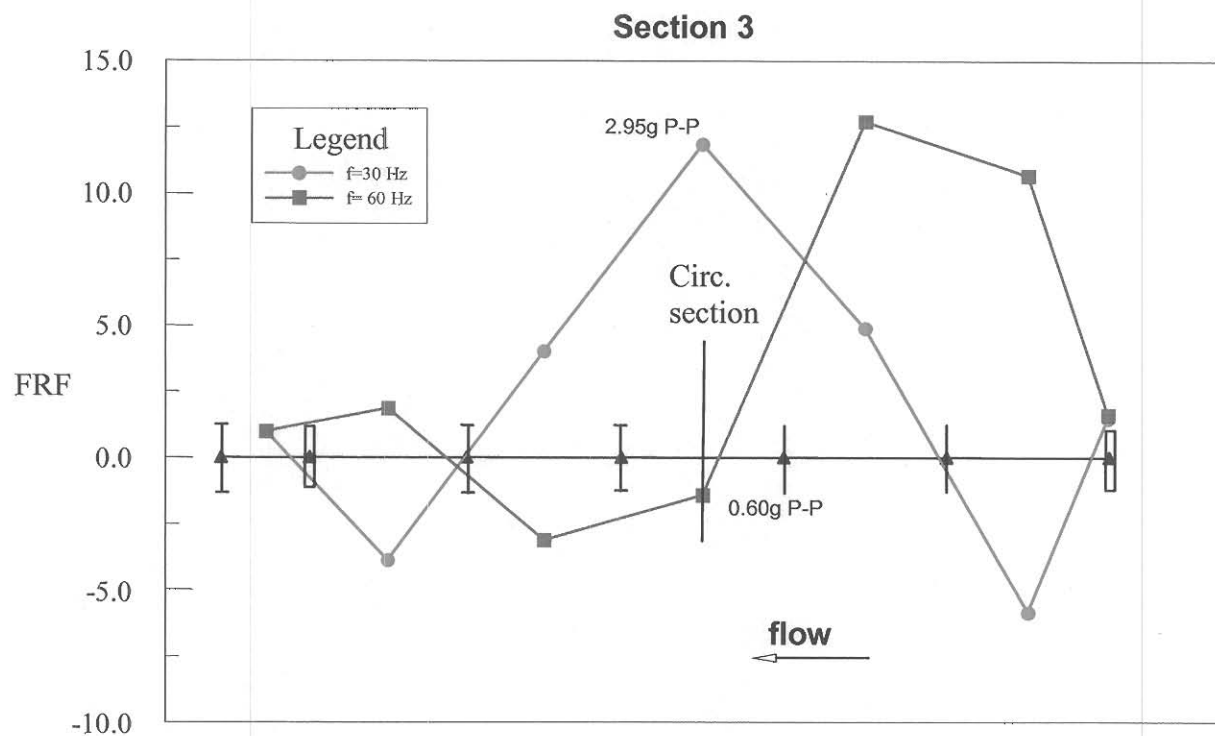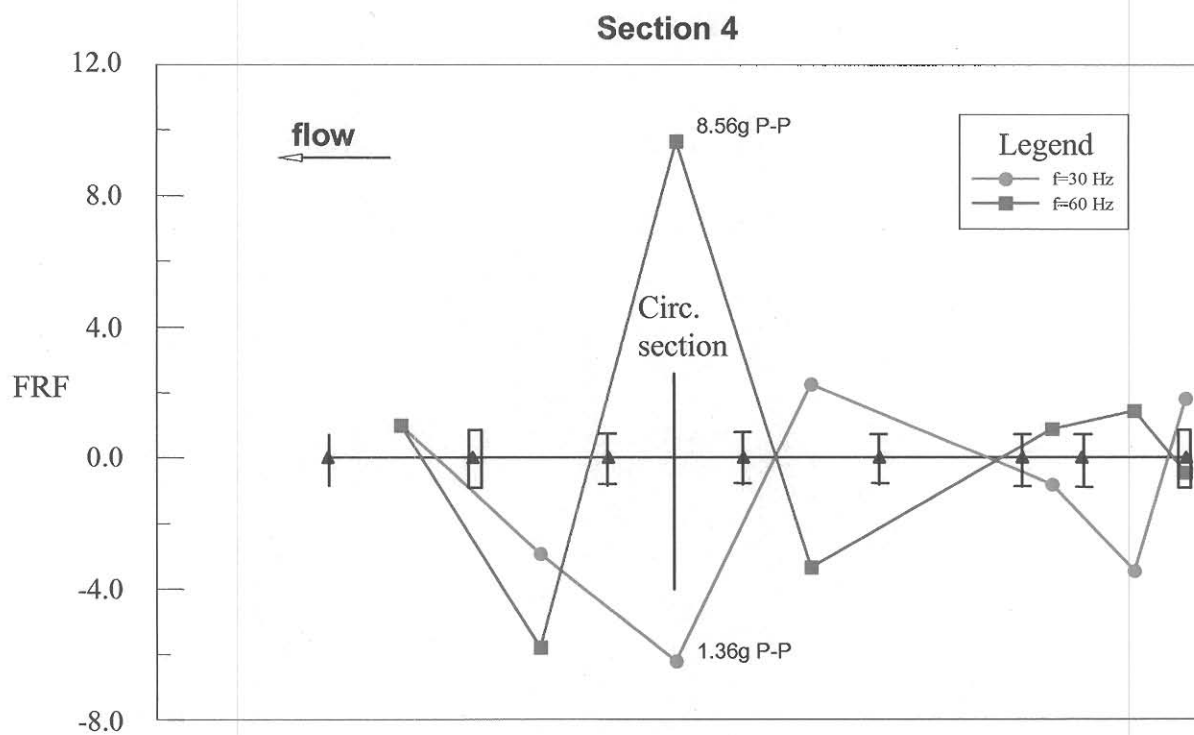
Figure 6: Details of P2 discharge pipe, showing stiffeners and supports.
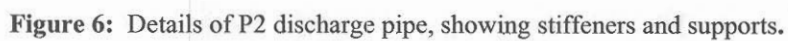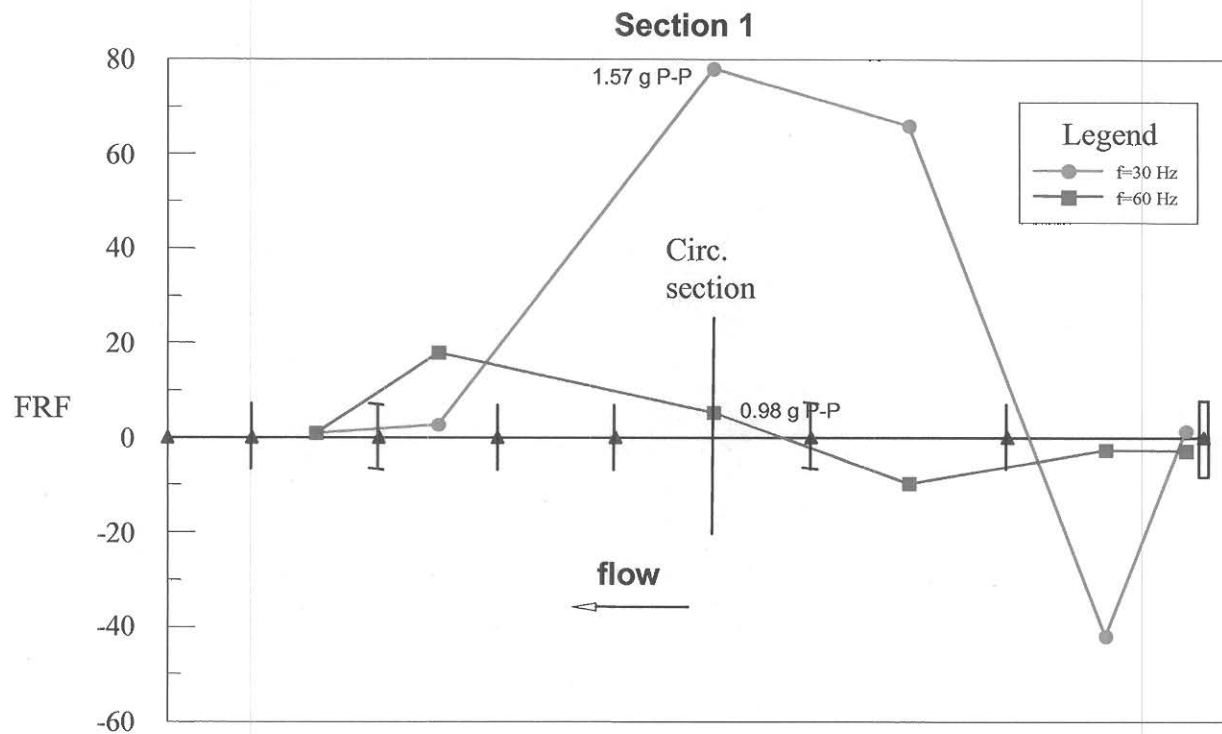
Section 1

Figure 7: Longitudinal ODS for section 1 of the P2 pipeline.
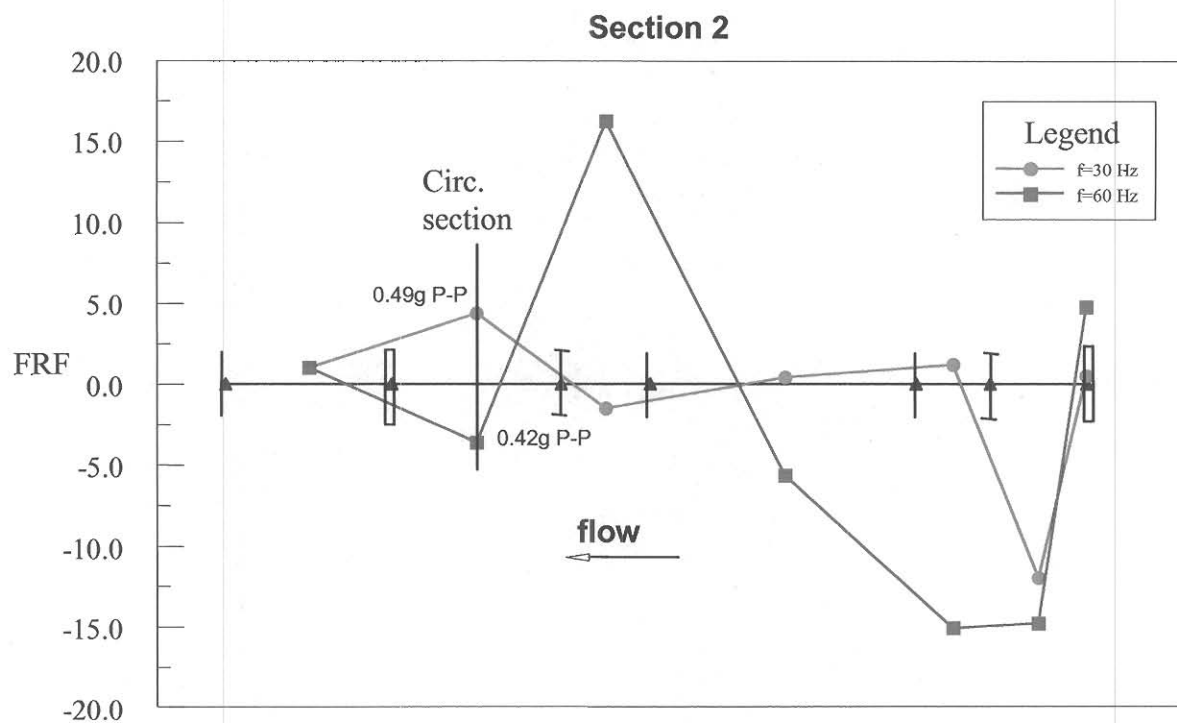
Section 2

Figure 8: Longitudinal ODS for section 2 of the P2 pipeline.

Section 3

Figure 9: Longitudinal ODS for section 3 of the P2 pipeline.
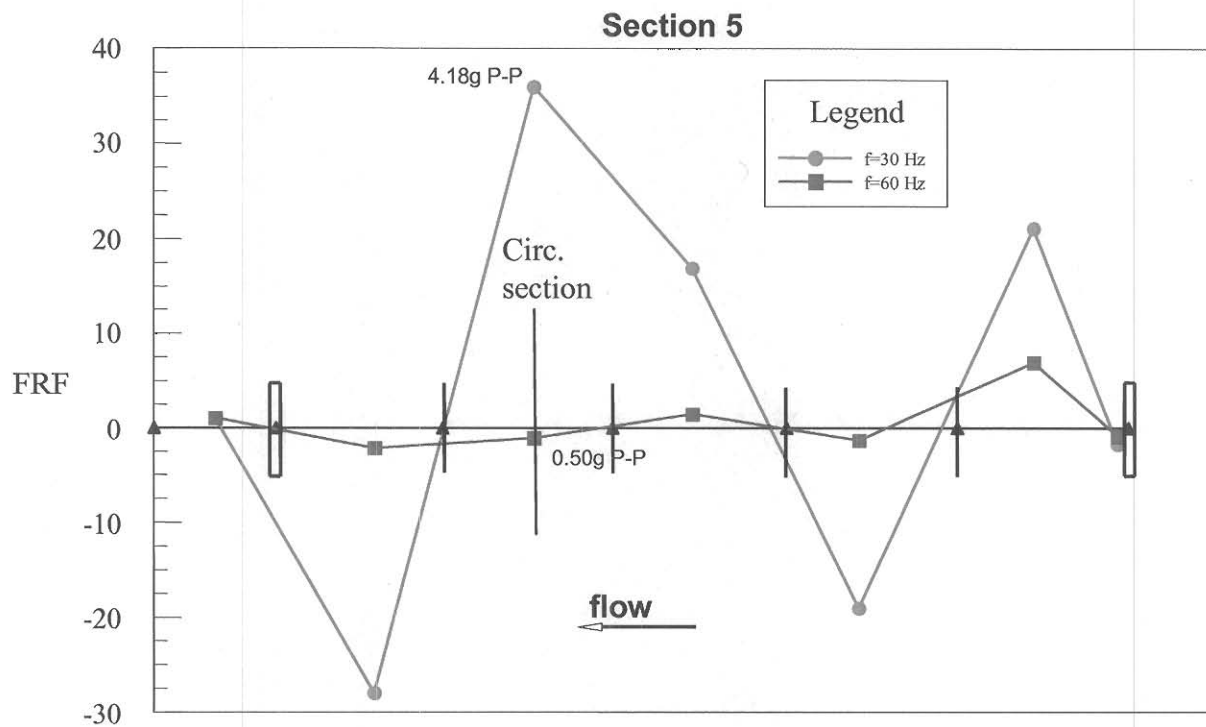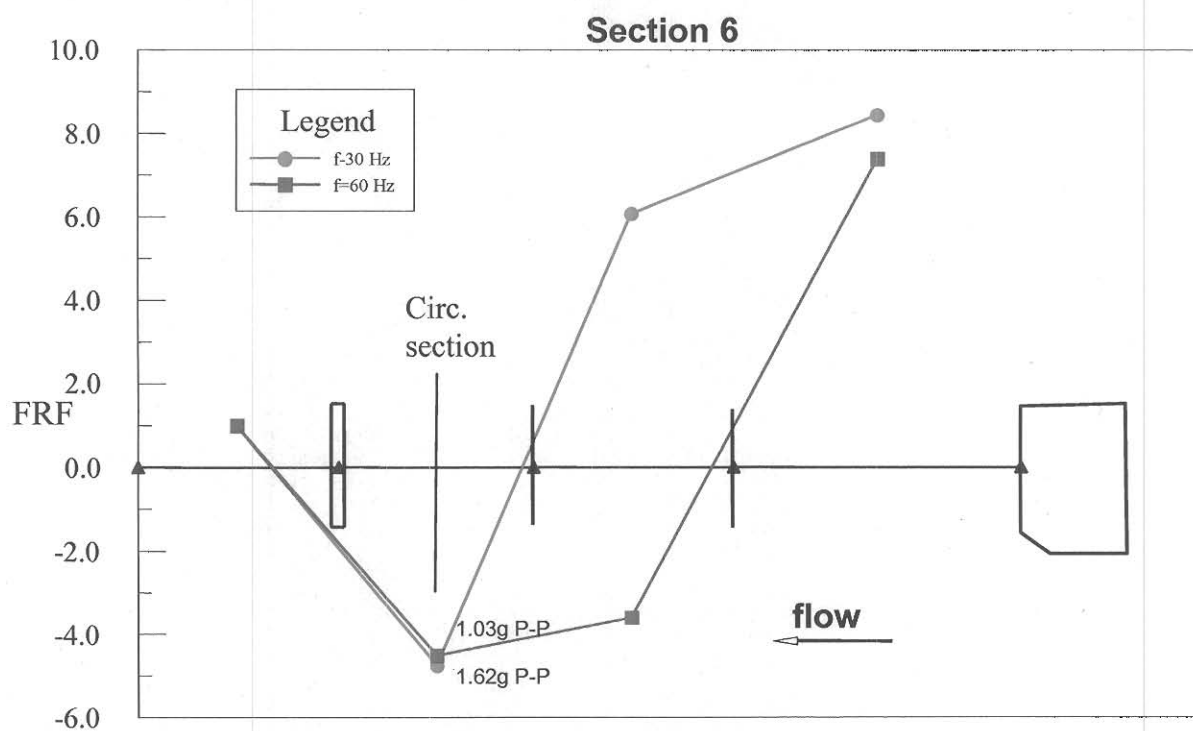
Section 4

**Figure 10:** Longitudinal ODS for section 4 of the P2 pipeline.

Figure 11: Longitudinal ODS for section 5 of the P2 pipeline.



Figure 12: Longitudinal ODS for section 6 of the P2 pipeline.

Circumferential Accelerometer Survey

At the longitudinal location of the highest response, circumferential data were collected in a similar manner. Initially, seven accelerometers were placed at 10-degree spacing at the top sector of the pipe. We also collected data at sections 3-6 at 5-degree spacing in order to see if higher modes were present. The circumferential operating deflection shapes are shown in figures 13-18.
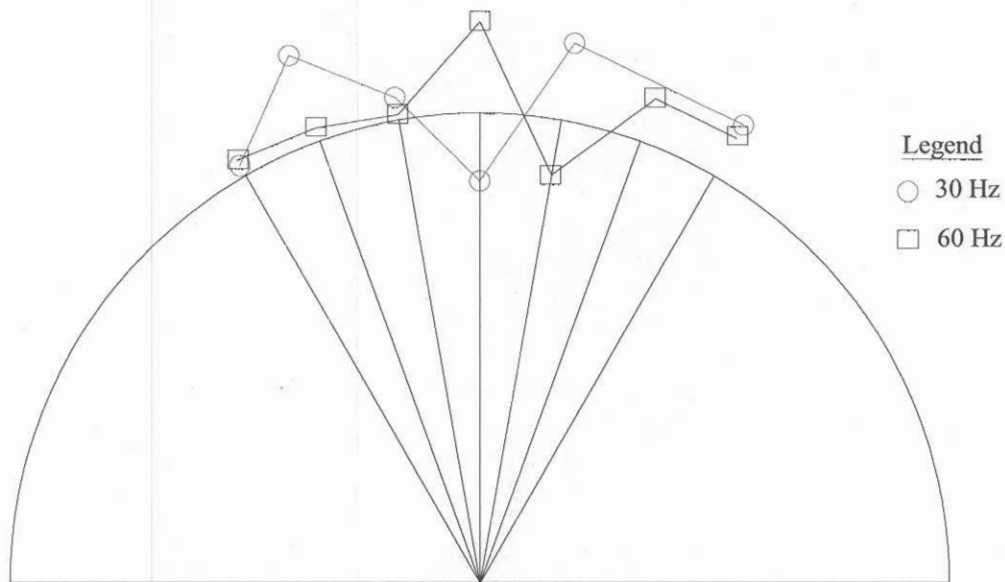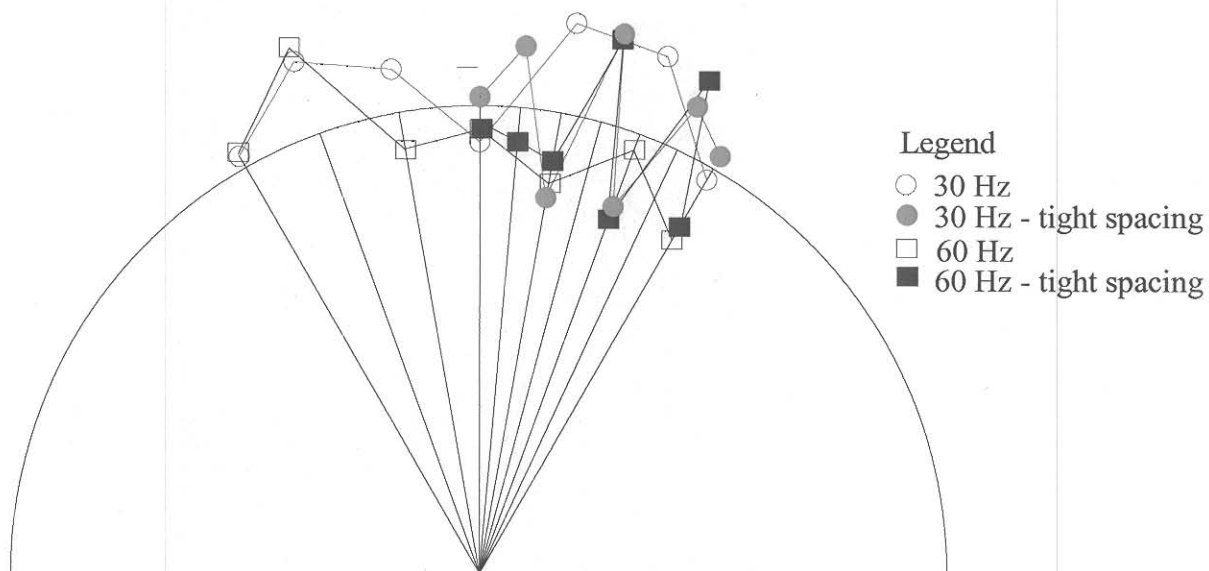

Figure 13: Section 1 circumferential Operating Deflection Shape.
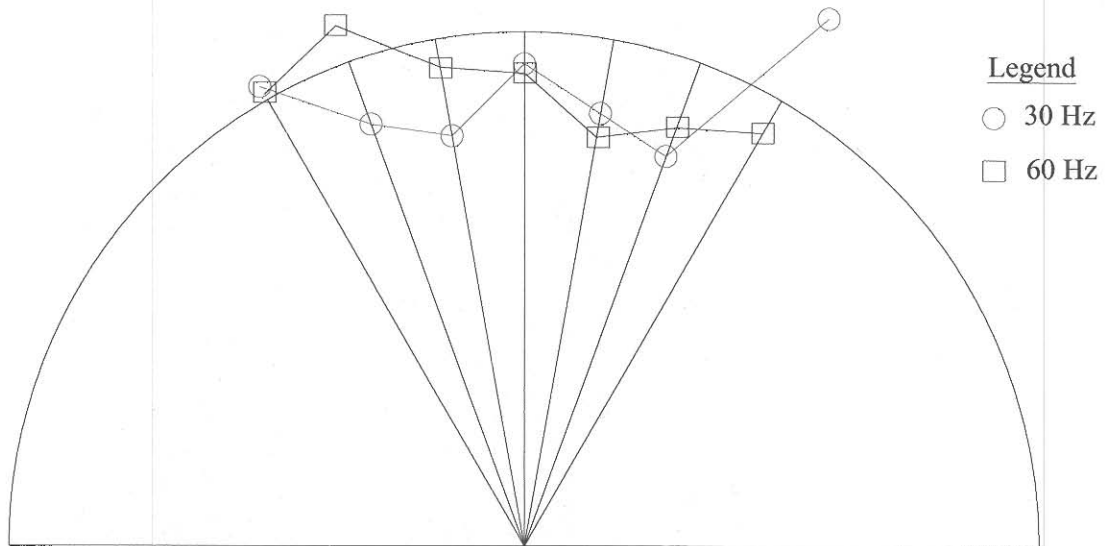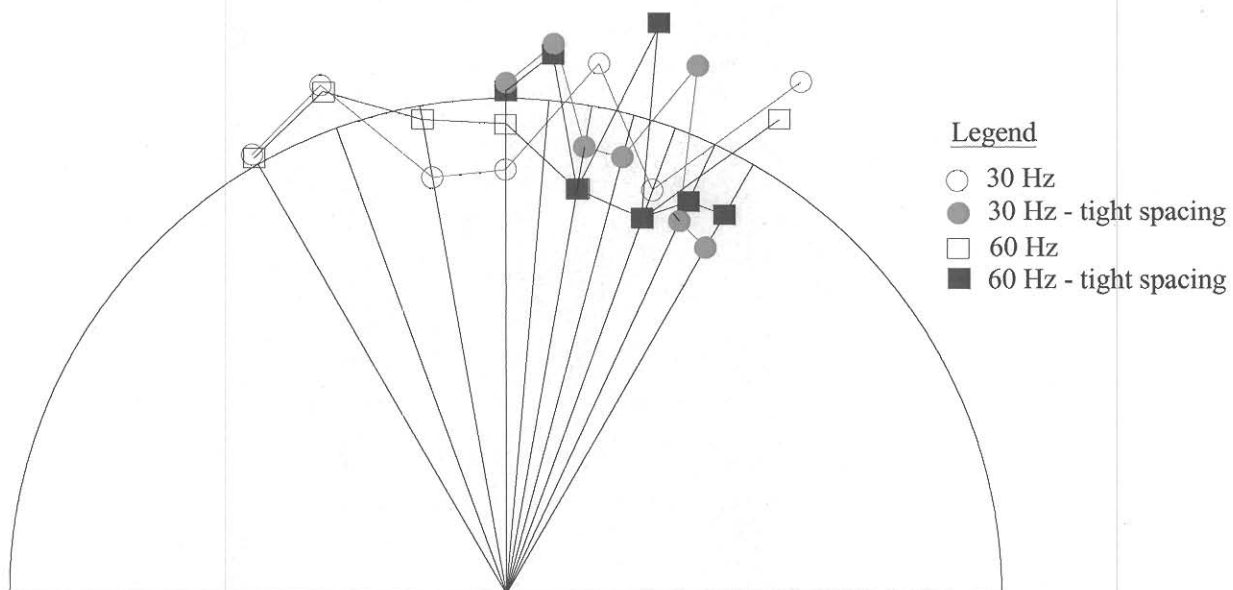
Figure 14: Section 2 circumferential Operating Deflection Shape.

Legend
○ 30 Hz
□ 60 Hz
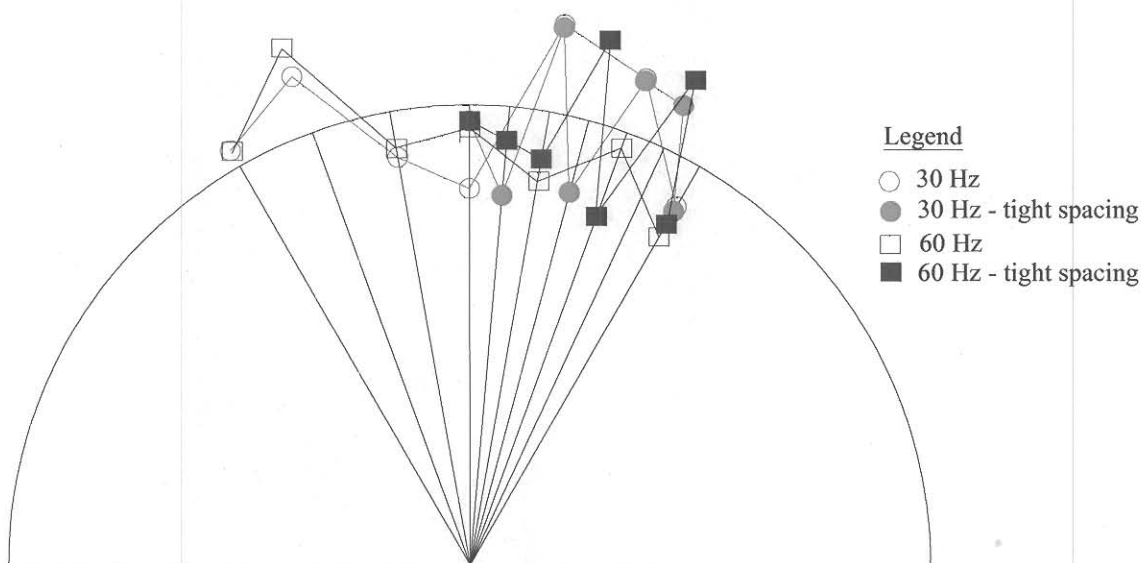
Figure 15: Section 3 circumferential Operating Deflection Shapes.

Legend
○ 30 Hz
● 30 Hz - tight spacing
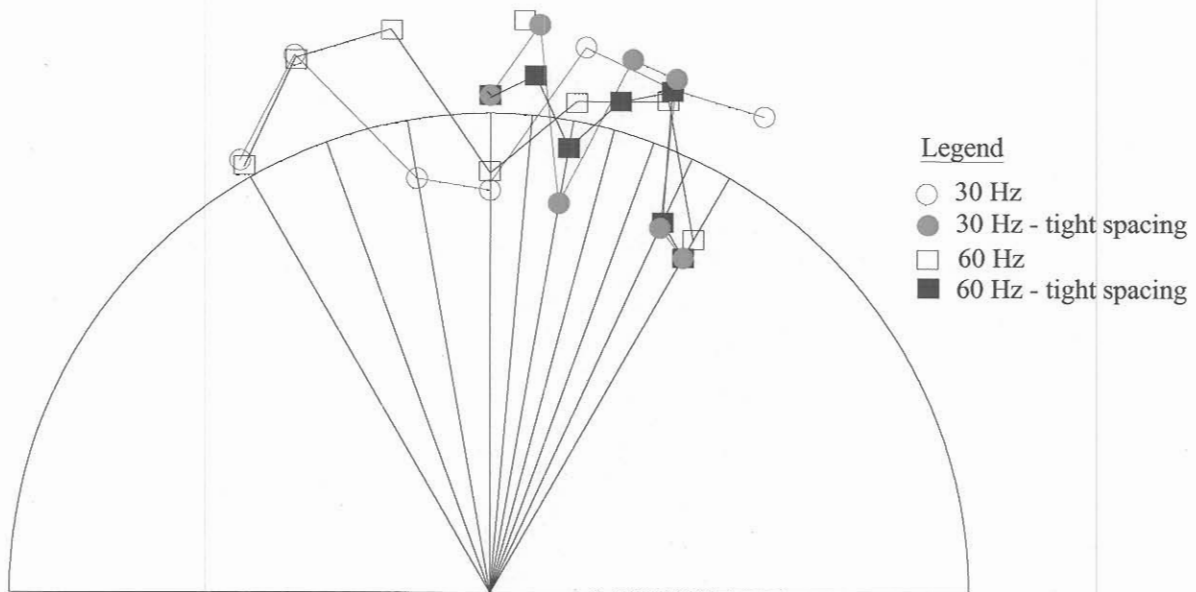□ 60 Hz
■ 60 Hz - tight spacing

Figure 16: Section 4 circumferential Operating Deflection Shapes.

Figure 17: Section 5 circumferential operating deflection shapes.

Figure 18: Section 6 circumferential operating deflection shapes.

All sections have relatively strong responses at 30- and 60-Hz.

Force Hammer Testing

We did limited testing with the force hammer. We did not have success using the hammer while the pump was operating so the only tests were performed with the pipeline evacuated. In figure 19, you can see a time series plot of the hammer blow and accelerometer responses at the highest responding section along the pipeline, section 4. Figure 20 shows a frequency spectrum of the response. The dominant frequency is very high, 410.6 Hz, and not in the range of the blade-passing-frequency even when the added mass of the fluid is accounted for. However, there are a couple of peaked responses that could be in the range of the 30- and 60-Hz operating responses, 51.6 Hz and 68.4 Hz. It seems likely that the 68.4 Hz in air could reduce and couple with the 1st harmonic of the blade-passing-frequency, 60 Hz when the discharge pipe is operating. The modal shape at f=68.4 Hz is shown in figure 21.
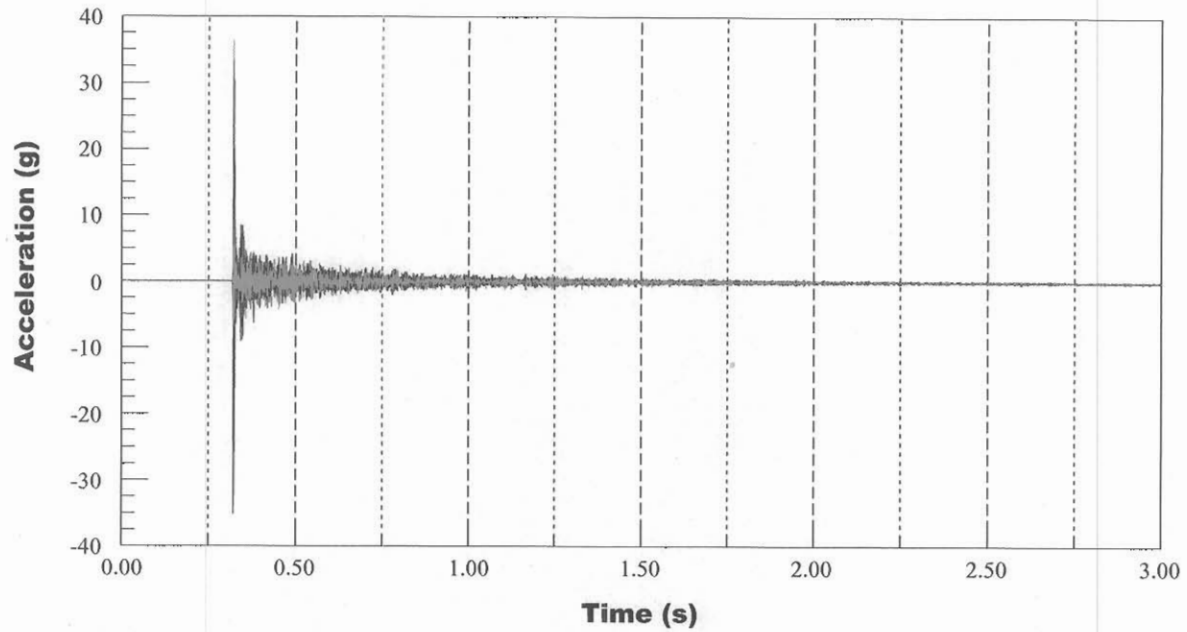
Figure 19: Time series of a hammer blow to the P2 discharge pipe, section 4, in air.
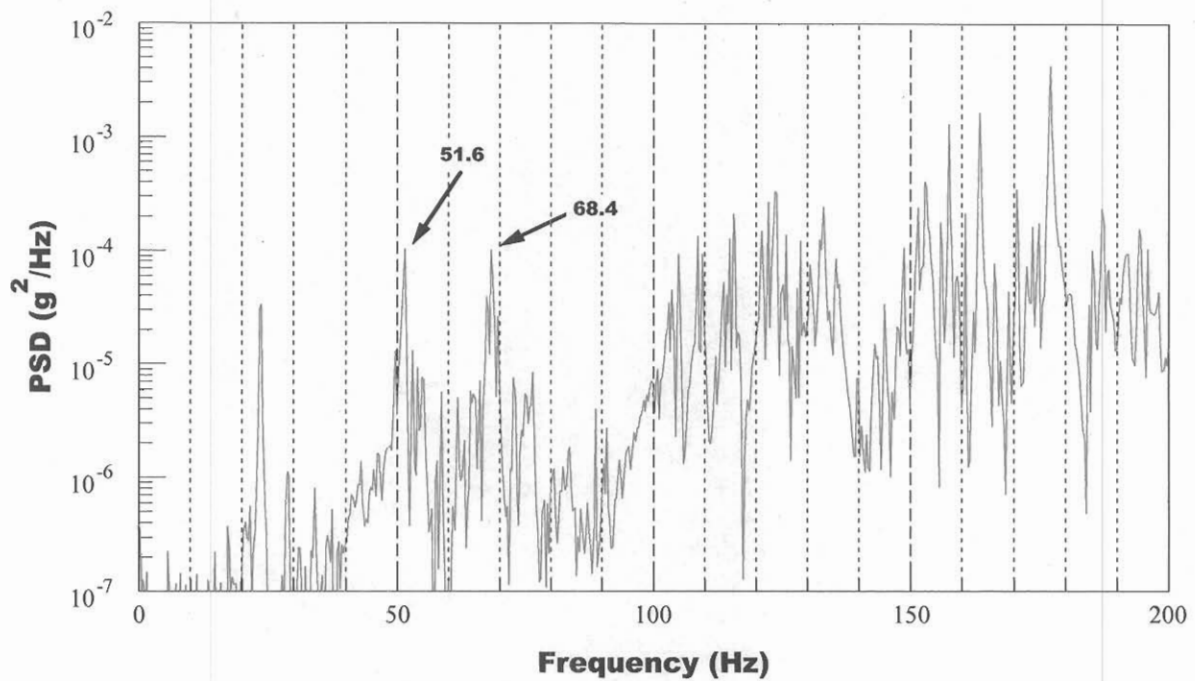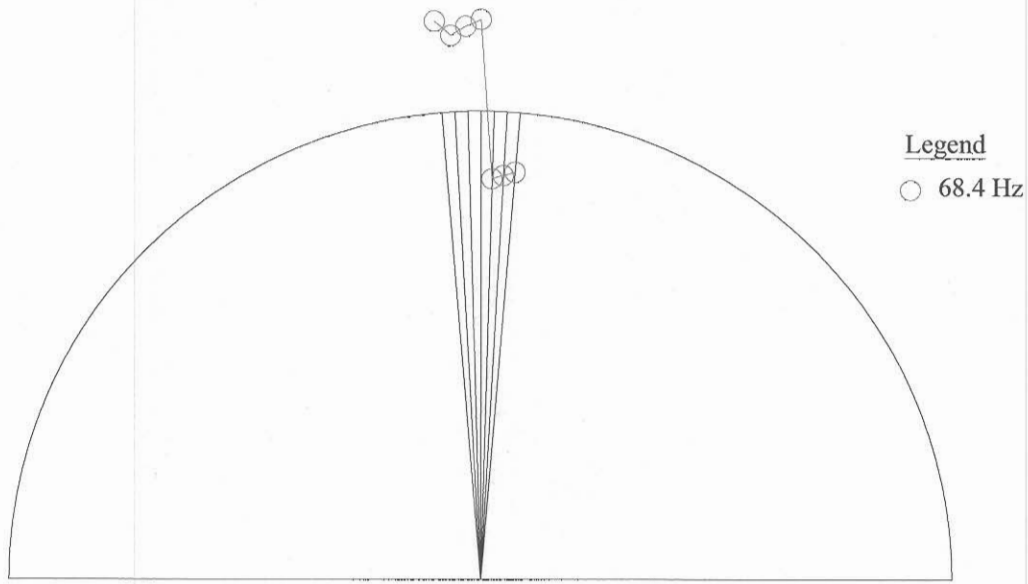

Figure 20: Power spectral density of the time series in figure 18. Dominant frequencies are very high; however there are a couple responsive peaks at 51.6 Hz and 68.4 Hz that could reduce with the added mass of the fluid.

Figure 21: Modal shape from hammer blow with pipe empty.

Strain Gages and Operational Stresses

Three operational tests were performed with the strain gages in place:

1. Startup of pump P2
2. Steady operation of P2
3. Shutdown of pump P2

For the steady stress operation, a rainflow counting analysis was performed on the time series. This data featured 614400 samples collected at 1000 Hz, spanning 10.24 minutes.

P2 Startup

Figure 22 shows the time record during startup of P2. Strain gage no.2 was not functioning properly so it is not shown. The power spectral density (PSD) is shown in Figure 23.
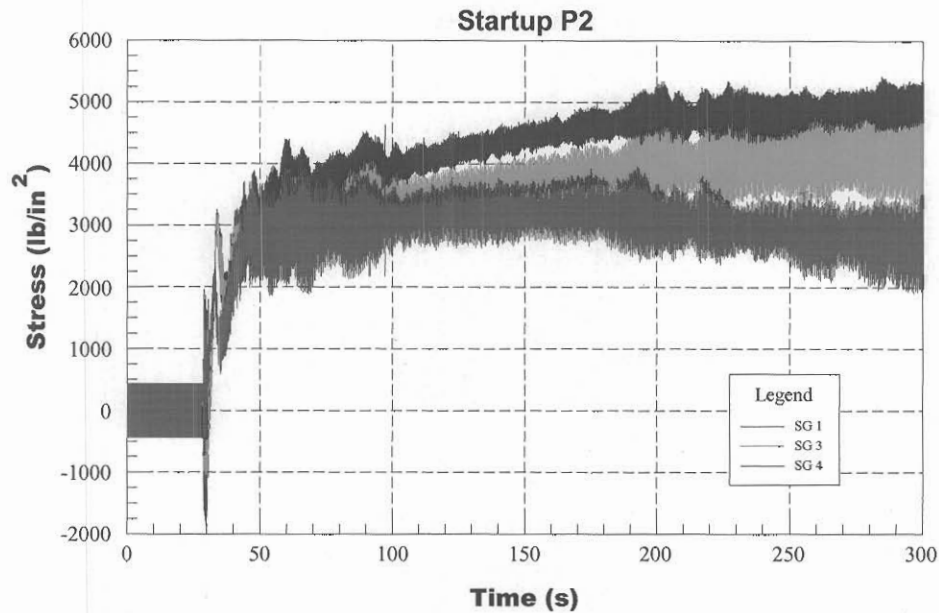

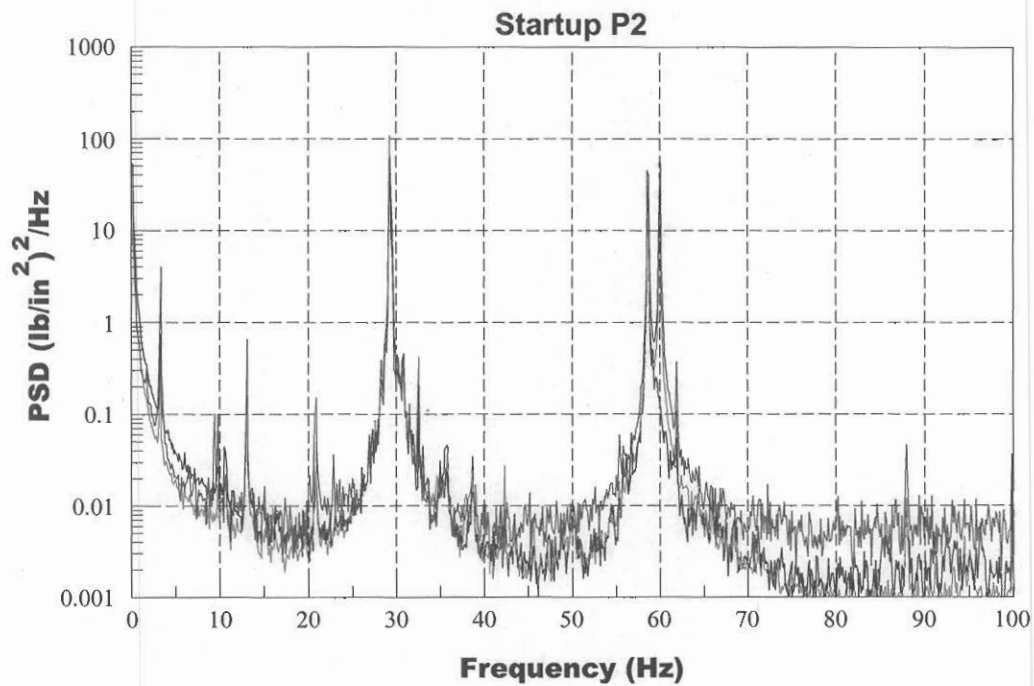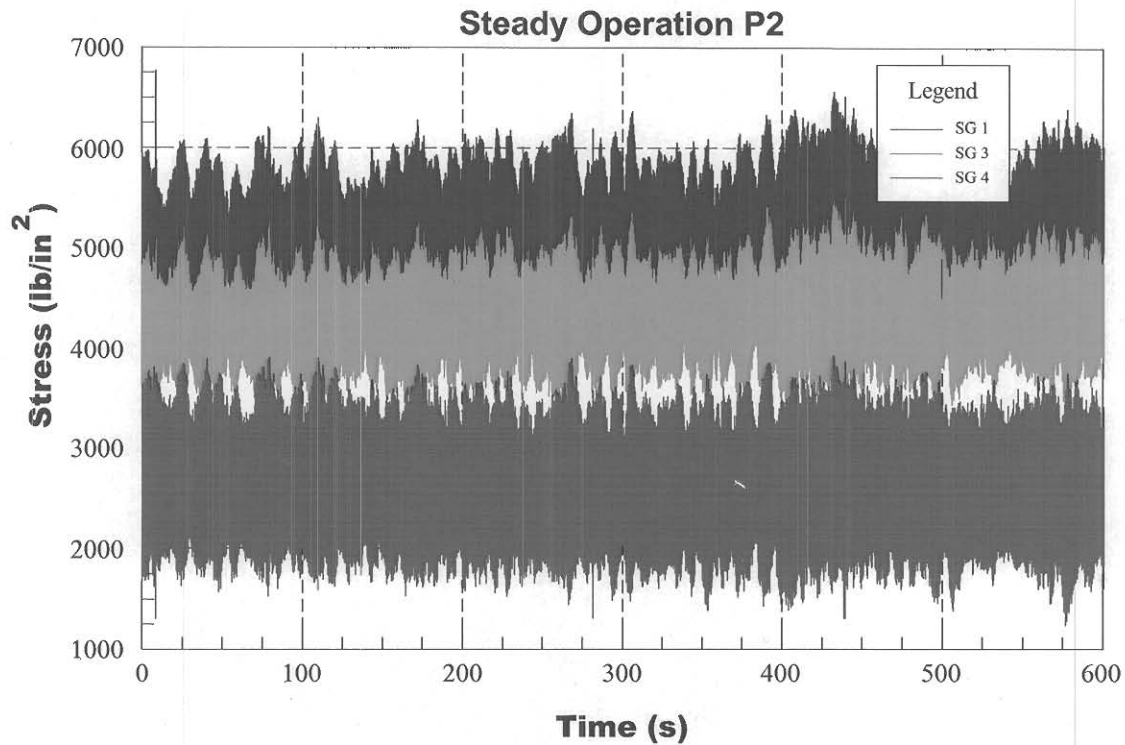**Figure 22:** Startup time series of stresses in section 4 near stiffener 16.

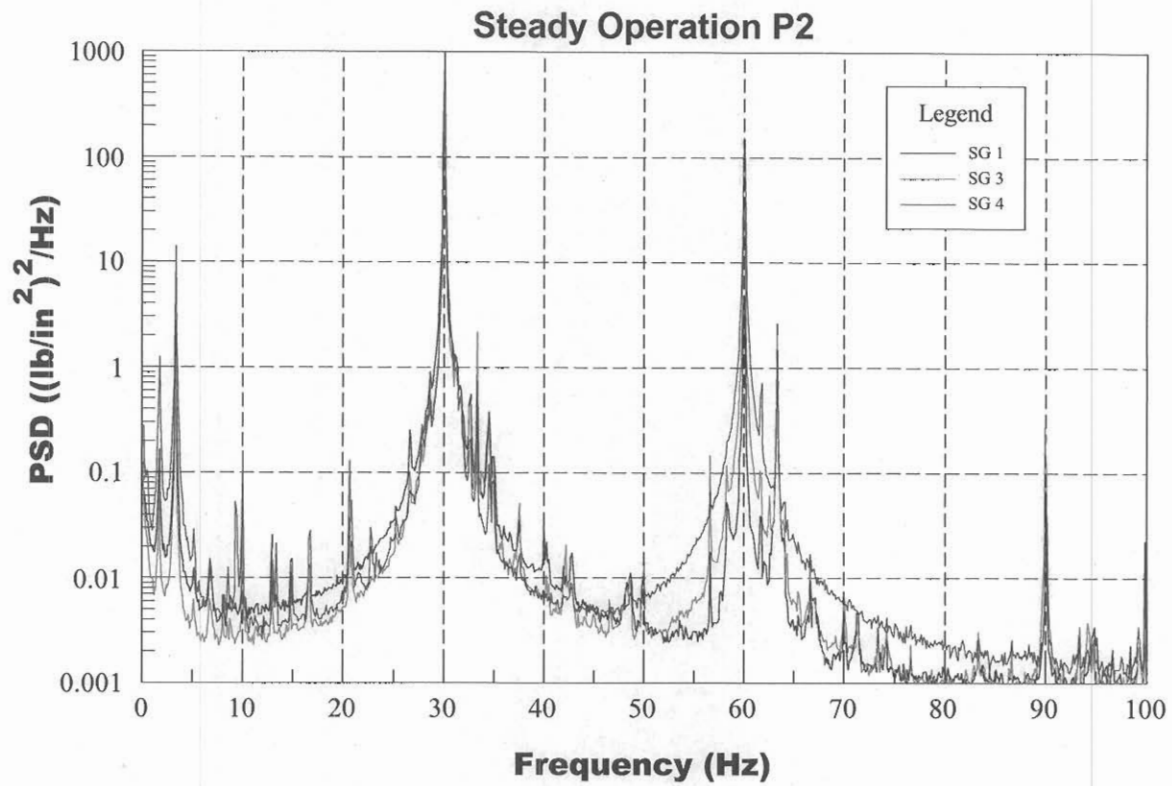**Figure 23:** Power Spectral density of stresses during startup of P2.

Steady Operational Stresses

Steady Operation P2

Figure 24: Steady operational stresses on P2. Mean stresses are: gage 1 - 5113 lb/in^2, gage 3 - 4339 lb/in^2, gage 4 - 2486 lb/in^2.

Figure 24 shows a time history of the steady operational stresses. The power spectral density of the steady stresses is shown on figure 25. In the 10.24 min time series shown above, we performed notch filtering to look specifically at the fluctuating component of the stress over this time period at 30- and 60-Hz. The maximum peak-to-peak values of the fluctuating component of the stresses as well as the RMS values are shown below.

Gage No.	P-P stress @ 30 Hz	P-P stress @ 60 Hz	RMS stress @ 30 Hz	RMS stress @ 60 Hz
1	1827.3 lb/in^2	1387.8 lb/in^2	347.0 lb/in^2	148.1 lb/in^2
3	819.3 lb/in^2	951.9 lb/in^2	247.9 lb/in^2	180.1 lb/in^2

Figure 25: Power spectral density of steady operating stresses near stiffener no. 16.
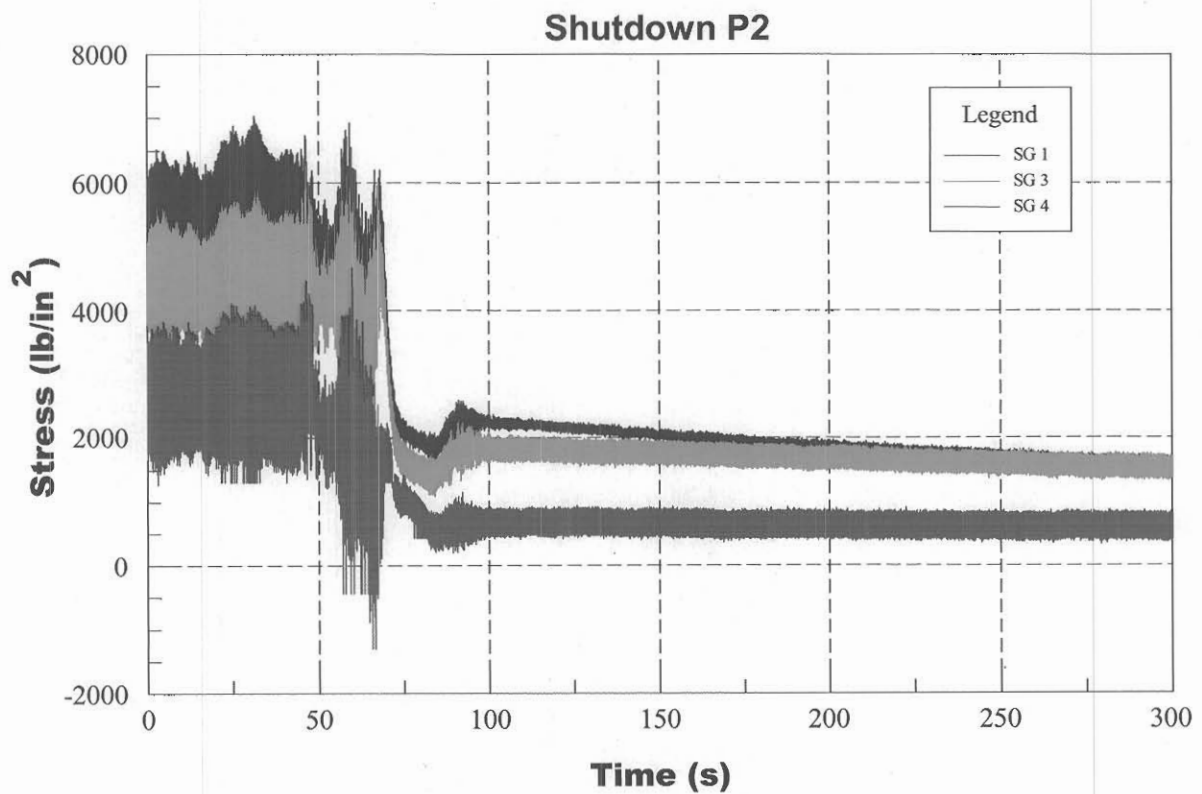
The operating deflection shape for an accelerometer spacing of 4 in between sensors and 3 in off the stiffener plate is shown in figure 26.
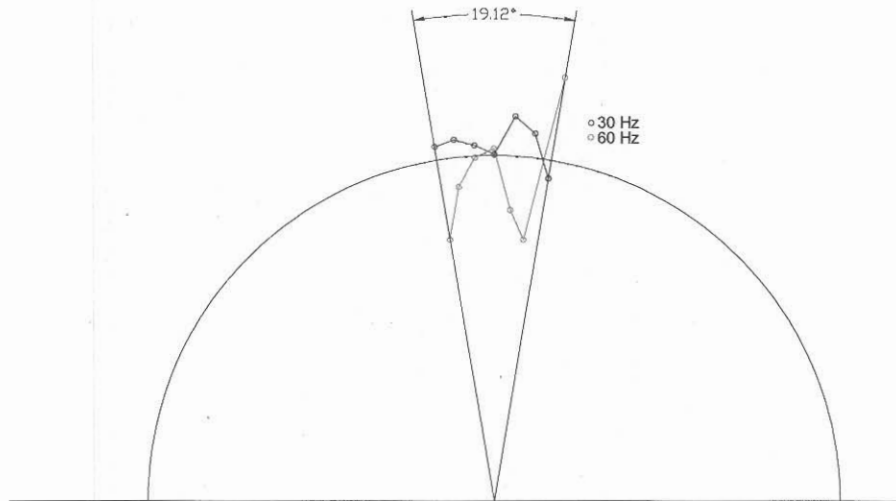
Figure 26: Circumferential ODS for tight accelerometer spacing during same time as steady operating stress were collected.

Shutdown of P2

Time record of the stresses during pump P2 shutdown is shown in figure 27.

Figure 27: Time series of stresses at stiffener No. 16 during shutdown of P2.

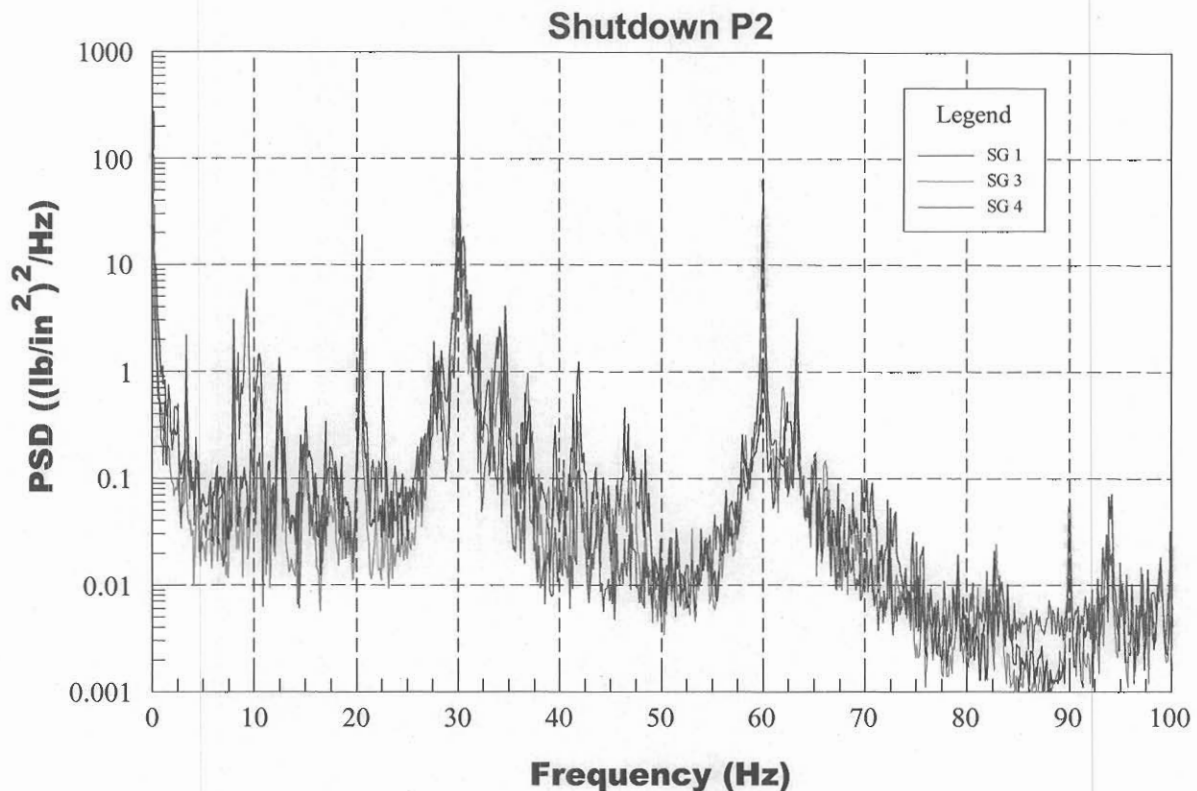The power spectral density of the P2 shutdown record is shown in figure 28.

Figure 28: Power spectral density of stress time records during shutdown of P2.

Mean Stress and Stress Fluctuations During Steady Operation

The mean stresses were computed from a 10.24 minute time record that was collected at 1000 points per second, yielding 614,400 samples. Strain gage 1 mean was 5113.5 lb/in^2, strain gage 3 mean was 4339.2 lb/in^2, and strain gage 4 mean was 2485.5 lb/in^2. A rainflow counting analysis was also performed on this time series. The rainflow counting algorithm is the currently accepted method for determining the stress time functions necessary to evaluate fatigue life. We used the implementation of the algorithm that is used in DasyLab 7.0. Results of the rainflow counting appear in figure 29.
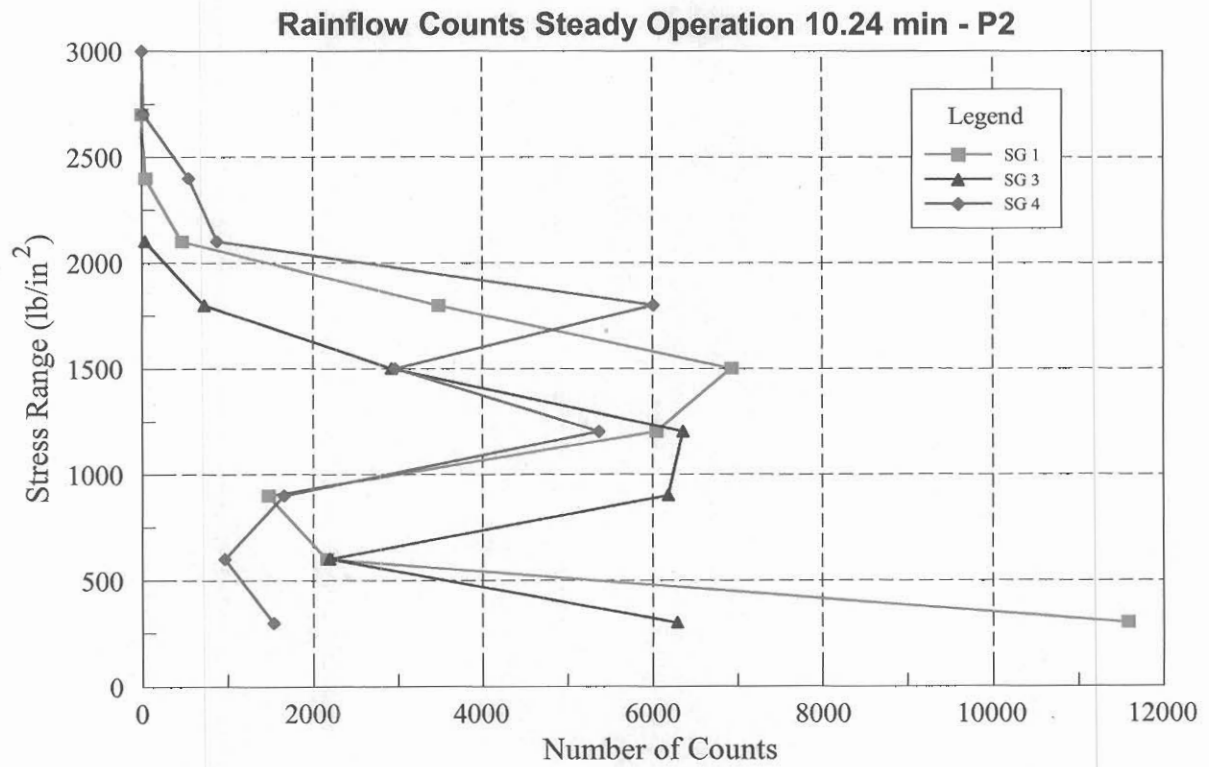
Figure 29: Results from the rainflow counting algorithm showing stress ranges used in fatigue life determination.